CHRONIC HEALTH IMPACTS OF VOLCANOGENIC FLUORIDE – LESSONS FROM A VANUATU CASE-STUDY

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Introduction – volcanic degassing hazards
Active volcanoes release significant quantities of various chemicals into the atmosphere through ash eruptions, eruptive degassing and lower-level passive flank emissions. The emissions can be purely dry gas, or form aerosols or adherents on ash particles. Following H₂O, CO₂, SO₂ and Cl; Fluoride (F) is one of the common constituents of volcanic gas (Symonds et al., 1994) and has been repeatedly implicated in human and animal morbidity and mortality. The earliest, and perhaps the most famous accounts of acute and chronic fluorosis in cattle as a consequence of volcanic activity come from Iceland (Roholm, 1937). The eruptions of the Laki Fissure in 1874-1875, and Hekla in 1947 and 1970, caused extensive animal mortality when gas aerosols or ash-fall coated pastures (Óskarsson, 1980). Grazing animals tend to ingest substantial quantities of soil when grazing, and ash-coated pastures significantly increase this intake, which leads to the development of fluorosis. This process has also been documented in many other areas of the world, including in New Zealand, when the 1995-1996 Ruapehu eruptions resulted in thousands of sheep deaths due to acute fluoride toxicity (Cronin et al., 2003a).

The most dramatic cases of mass human fatality from volcanic gases have been limited to sudden releases of CO₂ from stratified crater lakes or geothermal fields, such as in the Cameroon’s (e.g. Koenigsberg et al., 1987). Other elements, such as Mercury, Radon and Sulphur have also been implicated in long-term chronic health impacts in slowly degassing geothermal areas. However, the effects of volcanic F on human health have never been quantified, leading us to the overriding objective of this study:

To quantify the chronic human-health hazards of volcanic degassing at a constantly active volcano and compare and contrast this to areas where volcanic impacts are sporadic.

Here we report the first-phase of this study – an attempt to quantify the human health impacts of volcanic fluoride in a high-dose area with similar volcano-tectonic environment to the North Island of New Zealand.

Case-Study Ambrym Volcano, Vanuatu
Ambrym is an ocean-arc volcanic island in Vanuatu and is configured about a centrally-located summit caldera (McCall et al., 1970). The caldera has several open vents, including the two main craters of Marum and Benbow. Volcanic activity here has been occurring semi-continuously, in varying degrees and styles, for at least three hundred years. A continuous feature of the island is a volcanic plume of gas with low ash content; ash eruptions occur on cycles of days-months. The petrology and geochemistry of this volcano is consistent with its subduction-related tectonic setting and the erupted compositions are fairly uniformly “normal” calc-alkaline basalts (McCall et al., 1970).
The predominance of the southeast trade winds typically directs the volcanic plume toward the western half of the island during the dry season. Somewhat ironically, the greater part of Ambrym’s current 9000-strong population lives beneath this plume, although the variability of winds during the wet season ensures that no area of Ambrym is entirely immune from the volcanic emissions. Ambrym’s degassing leads to acid rain, dry gas deposition and aerosols that cause damage to food crops and vegetation (e.g. Eissen, 1991). Additional sporadic ashfalls exacerbate this impact. From an acute human health perspective, many past phases of high-level activity were accompanied by anecdotal accounts of acute respiratory and gastric symptoms – although these may not necessarily be caused by any particular plume element.

This phase of the project involves three methods of data collection:
1. **Gas measurements** – to quantify environmental inputs of F.
2. **Potable water survey** – to quantify potential human health hazards from volcanic F.
3. **Dental fluorosis survey** – to quantify impacts on population.

**Results**

**Gas Survey**

Two DOAS (differential optical absorption spectrometer) instruments (over UV bands) were used to measure elemental fluxes from the Ambrym plume, from aerial and ground-based surveys. In January 2005 this revealed emissions at a rate of 20 000 tonnes of sulphur dioxide per day, dropping to 14 000 tonnes/day in March. These measurements, coupled with satellite data (courtesy of Dr Simon Carn) demonstrated that Ambrym was the largest point source of SO\(_2\) on Earth throughout most of 2004/05. Direct measurements of fluoride emissions from the plume using FTIR (Fourier Transform Infrared) Spectroscopy were hampered by equipment failure at the crater edge. Hence, F release rates were calculated for the January visit using mass ratios of F/Br and Cl/Br in rainwater through the plume that was collected from the caldera during the period of DOAS plume measurements. Fluoride outputs were up to 1100 tonnes/day. Ambrym therefore appears to be an extremely important producer of volcanic elements to the surrounding environment, primarily due to its prodigious volumetric output of gas. Other measurements and observations over the past decades suggest that the high rates measured in early 2005 may represent near-extreme outputs for the volcano, and average outputs may be more like 2-4000 tonnes/SO\(_2\)/day.

**Potable water survey**

Ambrym inhabitants collect drinking water by harvesting rainwater, primarily from iron house roofs with storage in concrete water tanks. Samples collected within villages directly from rainfall on Ambrym over several years contained between 0.06 up to 6 ppm F; high values being when rain falls directly through an overhead plume. Rainfalls at the summit area, c. 5 km from the vents contain >100 ppm F. Tank and piped waters (from stream sources) sampled sporadically over the last 4 years have shown values up to 8 ppm F, which were considered to be of significant potential health hazard (Cronin and Sharp, 2002; Cronin et al., 2002). To put this into perspective, the World Health Organisation recommends a limit of < 1.0 ppm F in drinking water of tropical climates. In January 2005, over 150 water tank samples were found to contain between 3 to 11 ppm F (Fig. 1). Other major water sources were also high, including: streams, 2-8 ppm F; shallow ground wells, 2.4-2.8 ppm F; and coconuts, 4-10 ppm F.
Figure 1: Concentrations of fluoride in 154 drinking water samples from West Ambrym in January 2005. Diets with above 4 ppm F can cause skeletal fluorosis (WHO, 1984).

Dental survey
In humans, ingested fluoride is rapidly digested and while some of it is excreted, large proportions of it are deposited primarily in bones and teeth, particularly for children where growth rates are high (WHO, 2002). In teeth, fluoride affects the enamel as the tooth is developing; essentially this is during the first five years of life, before tooth eruption. The fluoride is incorporated into the apatite crystals of the subsurface enamel, forming fluorapatite. This alters the structure of the enamel and in doing so, increases enamel porosity. This dental fluorosis is observed macroscopically by chalky or white flecks, striations or mottling patches or areas on the tooth surface. Brown stains or pitting of dentition is an indication of more extreme levels of over-exposure (WHO, 1984). Dental fluorosis is the first visible sign of over-exposure to fluoride and starts to be encountered in a community where levels of fluoride in drinking water are 1-2 ppm (mg/l). It is also a convenient non-invasive means of quantifying impacts of fluoride over-exposure in populations.

The Dean’s Index of Fluorosis (Dean, 1934) is a measurement tool for the classification of dental fluorosis developed by a dentist in the USA. It is a visual assessment scale that involves looking at children’s teeth aged 12 - 14 years who, at this age, have most if not all of their adult/permanent dentition in place. According to the degree of dental fluorosis observed in each child, one of the six categories of the Dean’s Index is assigned:
1. Normal: no signs
2. Questionable: few white spots or flecks
3. Very mild: white patches/mottling <25% tooth surface
4. Mild: white patches/mottling <50% tooth surface
5. Moderate: white patches or brown discoloration, all of tooth surface affected
6. Severe: dark brown discoloration, pitting of enamel, all of tooth surface affected

This system is one of the main tools used in dental fluorosis surveys (WHO, 1987). Our survey was carried out by individual examination of all tooth surfaces each survey subject, and notation of the degree of effect for each tooth. This gives more information than needed for the Dean’s index, and hence also allows two other forms of dental index to be later calculated. Children were surveyed voluntarily either in villages or schools.

**Figure 2**: Classification of 254 West Ambrym children using the Dean’s Index of Fluorosis (Dean, 1934).

We have surveyed populations across the entire island and in down-wind areas. Presented here (Fig. 2) are only the results from western Ambrym (where we anticipate highest impacts). In West Ambrym, 254 children aged around 9-15 years were surveyed in January and May 2005. Less than 10% of children show little or no effect of fluorosis, and the majority of children show moderate to severe impacts (Fig. 2). These dental results indicate a long-term input of volcanic F into the diets of these children, with the impact period being as these children’s teeth were developing (starting 15 years ago in the case of the surveyed children). There is nothing that can be done to ameliorate this effect now for these children. In the case of those with severe or moderate fluorosis (Fig. 3), tooth strength has been compromised and they may lose their teeth early. There is also some anecdotal evidence of social implications of having “west-Ambrym teeth”

More importantly from an ongoing health perspective, the level of dental impact shown and the ongoing high water F-contents suggest that skeletal fluorosis is also of potential danger in this area. This is a serious condition involving weakening of bones, development of bone-growth deformities, joint problems etc and in its severest form, the disease is crippling (WHO, 1984).
Discussion

Mitigation of Fluorosis hazard

Studies are still underway to characterise other dietary inputs of F for this population, however, based on international experience, these are expected to be only a small proportion of the intake via drinking water. Hence any mitigation of this fluorosis hazard has to centre around removing F from drinking waters; measures could include a combination of the following:

- Education and awareness to develop practices for disconnecting water supplies from enclosed reservoir tanks, and covering open tanks, to reduce the amount of fluoride accumulating.
- Filtration devices to remove excess fluoride. The problems with this method is that up to 600 individual tanks would have to be treated around the island, involving large costs, ongoing maintenance issues and other hazards from disposal of fluoride-rich waste.
- A potential longer-term solution for reducing F intake may be to derive water from deep wells, where natural filtration through soils is able to take place. Fluoride has a strong affinity for soils and binds strongly to volcanic soils and clay minerals (Cronin et al., 2000).

Implications for New Zealand

New Zealand does not currently have a long-term degassing volcano with anywhere near the same output as Ambrym. However, Ruapehu during its 15-month eruptive phase of 1995-96 commonly produced between 1000 and 5000 tonne SO$_2$/day, with some occasions exceeding >16 000 tonne/day (Christenson et al., 2000). These values are in the same order of magnitude as Ambrym, and based on its magma composition, the Ruapehu system probably produces proportionally more F than Ambrym (Cronin et al., 2003). In addition, the Crater Lake, while present acts as a store for gases from Ruapehu, which means eruptions through the lake have in the past been responsible for ash falls strongly concentrated in F and thus of high hazard to grazing animals and water supplies (Cronin et al., 2003). The mediating factor for long term fluorosis hazards in Ruapehu's case is the short period of high F supply to the environment. However, periods of 1-3 years may still have a significant impact on any children exposed at that time to higher levels of F in drinking waters. That many of our catchments are fluoridated to c. 1 ppm F for dental health reasons means that additions to this elevated base level could be significant.
Other potentially high producers of F to the downwind environment of the North Island could be Taranaki and Major Island volcanoes, both of which have magma compositions that favour higher F concentrations. The Taranaki system has commonly affected large areas of the North Island with past tephra eruptions due to its position with respect to prevailing winds. Recent work suggests that many of its past eruptive periods may have lasted for several years or even decades (e.g. Cronin et al., 2003b). Such long-term eruptions from Mt Taranaki – similar to the Montserrat-like activity are the most likely scenarios to pose a dental fluorosis hazard to children in New Zealand.

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